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Importance of decadal scale variability in shoreline response: examples from soft rock cliffs, East Anglian coast, UK

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Importance of decadal scale variability in shoreline response: examples from soft rock cliffs, East Anglian coast, UK

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Abstract

Rapidly eroding soft rock cliffs typically retreat at rates in excess of several metres per year, thus allowing the resolution of linkages between cliff dynamics and a range of climatic and marine forcing factors. New evidence from UK coastline of East Anglian coastline, southern North Sea shows that unprotected soft rock cliffs at three widely-spaced locations all show similar variability in retreat behaviour on decadal timescales, which we attribute to changing patterns of storminess in these decades. The 1990s were characterized by frequent months in which the North Atlantic Oscillation (NAO; a well-established measure of inter-annual climatic variability in North-West Europe) was extremely positive (more positive than +3) or extremely negative (more negative than -3), while the 2000s showed few occurrences of such extreme values. Depression tracks in positive NAO phases make the East Anglian coast prone to storm surges in which raised water levels result from deeply developed low pressure systems, generally associated with westerly air streams. In negative NAO phases the region is prone to easterly airflow which results in periods of strong onshore wind. Both phases are associated with high energetics in the forcing factors. Decadal-scale variability in cliffline retreat rates has implications for the practice of coastal management and policy making and suggests that cliff system responses to global environmental change are not simply driven by secular sea level rise.

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Introduction

The coastal zone population is estimated to be as much as 10% of the global population (McGranahan et al. 2007) and predicted to increase to 1.8 – 5.2 billion by 2080s (Nicholls et al. 2007). At the same time, the risks associated with global climate change are making coastal locations increasingly vulnerable for human lives and livelihoods and creating considerable challenges for robust, sustainable coastal management (Nicholls et al. 2008, Cooke et al. 2012, Moser et al. 2012). The likely impacts of secular sea level rise (Church and White 2006), expected to accelerate in the coming decades (Meehl et al. 2007, Ranasinghe and Stive 2009, Nicholls et al. 2011) has been the focus of considerable scientific debate (e.g. Dawson et al. 2009, Nicholls et al. 2007, Thorne et al. 2007). At the same time, there has also been a considerable interest in potential near-future changes in storminess consequent upon ocean warming (Field et al. 2012) and in the likely consequences of intensified tropical (Mousavi et al. 2011) and extra-tropical (Ciavola et al. 2011) storm impacts on coastlines. Monitoring and modelling shoreline response has mirrored these concerns, being directed towards both long-term responses to sea level rise over decadal (e.g. Ranasinghe and Stive 2009, Anthoff et al. 2010) or millennial timescales (e.g. Woodroffe and Murray-Wallace 2012) and short-term adjustments to single events or annual cycles of change in response to seasonal wave or rainfall variability (Van Rijn et al. 2003, Davidson et al. 2010). Not only is it difficult to couple understanding at these two different timescales (e.g. Cowell et al. 1995, Stive et al. 2009) but such a bi-polar approach also obscures the potential importance of inter-decadal variations in climate to shoreline dynamics (Montreuil and Bullard, 2012). Such intermediate timescales are important because they sit, at their upper bounds, within the time period often considered by climate models (typically to 2100 AD) and, at their lower bounds, by the periods over which strategic planning decisions are made. Decadal scale climate change has recently been observed to involve significant variability in both storminess (Wang et al. 2009) and sea level (Philips and Crisp 2010). Decadal variations in storminess have been shown to affect overall shoreline position (e.g. Esteves et al. 2011), beach sediment volumes (Thom and Hall 1991), foredune development (McLean and Shen 2006) and intertidal mudflat elevations (Kirby and Kirby 2008); in this paper we concentrate upon the effect of climatic variability on the geomorphology of soft rock cliff faces and sediment supply to the nearshore zone.

Viles and Goudie (2003) identify some 15 different climate oscillations of potentially high importance for landscape change, with characteristic time periods varying from less than a century to millennia. They include the typical 4 year periodicity of El Nino Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) and the 65-80 year periodicity of the Atlantic Multidecadal Oscillation (AMO; see also Azuz-Adeath 2012). In this paper we concentrate upon the North Atlantic Oscillation (NAO), one of the dominant modes of Northern Hemisphere climate variability (Burningham and French 2012). Its positive phase is characterised by below-average atmospheric pressure in the region of the Icelandic Low and above-average pressure in the Azores. This leads to a strongly ‘Atlantic’ climate in NW Europe, with dominant south westerly airstreams and above average temperatures. In the NAO’s negative phase, the Icelandic Low and Azores High pressure systems weaken and migrate southward, resulting in a greater dominance of northerly and easterly winds and in more severe winters in northern and western Europe. A typical 6 to 10 year pattern of variability characterised the NAO in the second half of the twentieth century, replacing a much shorter, bi-ennial pattern during the earlier instrumental record (Jones et al. 1997). A major negative NAO phase occurred in the 1960s with a sustained positive phase in the 1980s (Hurrell 1995). Here we concentrate on the variations in the winter (October – March) NAO in the period 1992 – 2011.

Lateral retreat in soft rock cliffs at rates of typically over 1 m a^{-1} and sometimes over 10 m a^{-1}, up to four orders of magnitude faster than the most resistant rock types (French 2001), has attracted considerable recent attention. This interest has also tended to focus on either long-term past and future retreat (Hall et al. 2002, Walkden and Hall 2005, Walkden and Dickson 2008, Brooks and Spencer 2010, 2012) or has involved short-term detailed studies of retreat mechanisms, often from field observations (Collins and Sitar 2008, Young et al. 2009), in order to understand both marine and terrestrial process drivers (Brooks et al. 2012). The magnitude of system change, with typical shoreline translation rates of 10 - 100 m over a 10 year period, the rapidity of response to changes in environmental forcing factors, and the rapid adjustment to changes in input conditions (Hansom 2001, Trenhaile 2011) makes them ideal systems in which to assess the importance of inter-decadal climate change to coastal response.

Recent technological advances allow detailed quantification of shoreline change at an unprecedented level of spatial densification, both from field survey as well as from map and aerial photograph analysis (Moore 2000, Brooks and Spencer 2012). Specifically, the United States Geological Survey's Digital Shoreline Analysis System (DSAS) enables quantification of shoreline change along shoreline lengths rather than simply at-a-point (Thieler et al. 2005, Addo et al. 2008). Such an approach was used previously to study the retreating cliffs of Suffolk between Benacre and Southwold (Figure 1) to gain insight into the specific nature and causes of shoreline retreat (Brooks and Spencer 2010, Brooks et al. 2012) in order to predict how the shoreline might respond in future (Brooks and Spencer 2012). That work demonstrated the utility of the DSAS methodology. In this paper we extend the analysis to the wider region of East Anglia, involving detailed analysis of the retreating soft rock cliffs at two further sites: Walton-on-the-Naze, Essex (Gray 1988) as well as at Weybourne-Sheringham, Norfolk (Clayton 1989) (Figure 1). By seeking a regional signal in cliff retreat we aim to understand the more general controls on cliff retreat so that future management practices and policies can be based on a more grounded set of regional controls. Initially we quantify longterm historic retreat rates to provide a context for what has occurred in the recent period for which data are readily available. Subsequently we look at decadal-scale variability in retreat rates and quantify the associated variability in sediment release, before finally seeking regional explanations for variability on this timescale.

Location and regional setting

Retreating soft rock cliffs characterise long sections of the UK eastern coast bordering the southern North Sea, particularly along the coast of Holderness, north of the Humber estuary, and within the region of East Anglia, between The Wash embayment to the west and the margins of the Thames estuary to the south (Figure 1). Much of this soft rock cliffline is now protected, but where these cliffs are exposed to marine and terrestrial processes, average retreat rates since the end of the nineteenth century have exceeded 1 m a^{-1} (Williams 1956, Steers 1964, Clayton et al. 1983, Cambers 1975, Gray 1988). Here we concentrate upon three study sites in the north, central and more southern parts of this region.

Weybourne to Sheringham, North Norfolk

The cliffs of North and North East Norfolk comprise a 33 km stretch of retreating cliffs, although protected to varying extents in the east. In this paper we investigate in detail the unprotected section between Weybourne and Sheringham, a 3 km stretch of cliffs, being the highest and longest continuous cliff system of the three sites discussed in this paper. At this location the cliffs have an average elevation of 25 m (Clayton 1989). Here the chalk basement remains above sea level, although dipping eastward, and is overlain by Quaternary sediments (glacial till from the Anglian Stage) that exhibit a high degree of stratification (Boulton et al. 1984) (Figure 1a).

The Mean Spring Tidal Range (MSTR) is 4.23 m, with the highest astronomical tide at Cromer reaching 3.39 m ODN (= Ordnance Datum Newlyn which approximates to mean sea level); this site has the highest tidal elevations and greatest tidal range of the three sites. The cliffline is north-facing (4°E) and large (>5 m) onshore waves can be generated when winds are from the north (Chini et al. 2010). However, the cliffs are fronted by a relatively stable, steep pebble beach which protects a cliff base elevation of between 5 and 6 m ODN.

These cliffs have estimated geological retreat rates of ca. 1 m a^{-1} (Clayton 1989), dating from 5000 BP when sea level reached its current position. Recent measurements using historic maps have confirmed that this rate typified the first part of the nineteenth century, being 0.9 m a^{-1} between 1880 and 1967 (Cambers 1976).

Benacre to Southwold, Suffolk

The Suffolk cliffs have a different morphological setting, comprising a series of well-defined cliff sections separated by near-sea level saline lagoons, or Broads (Barnes 1989). There are 5 individual cliff sections (from north to south): Benacre, Covehithe, Easton Wood, Northend Warren and Easton Cliffs, ranging in elevation from around 5 m ODN to 15 m ODN. They are composed of Pleistocene Norwich Crag deposits which overlie earlier Late Pliocene-Early Pleistocene beds (Gibbard et al. 1998, West 1980). There are alongshore differences in the Plio-Pleistocene stratigraphy which potentially play a role in the precise manner in which the cliffs retreat (Brooks and Spencer 2010) but the predominantly sandy/silty Pleistocene deposits overlying a more resistant clay basement provides a similar general stratigraphic setting to the cliffs of North Norfolk.

The MSTR is 1.94 m at Lowestoft, lower than for the other two sites, with Highest Astronomical tide (HAT) being 1.48 m ODN. The cliffs are orientated in a northeast-southwest direction, so waves that are not fetch-limited can be generated when winds are between 330° and 170° (Carr 1979). However, the wave climate here is more moderate than in Norfolk. Wave heights rarely exceed 2 m (Pye and Blott 2006, Marine Aggregate Levy Sustainability Fund 2009) and in the north of the study area, waves at the coast are attenuated (Stansby et al. 2006) by sandbanks and sandbars in subtidal complexes that extend well offshore (Carr 1981, Reeve and Fleming 1997, Pye and Blott 2006, Horillo-Caraballo and Reeve, 2008). Unlike North Norfolk, the steep, narrow cliff-fronting beaches show marked seasonal fluctuations in both elevation and volume (Lee 2008).

Long-term retreat rates for the Suffolk cliffs are considerably higher than for North Norfolk, being around 5 m a^{-1} in the north at Benacre declining to around 2 m a^{-1} in the south (Cambers 1976, Brooks and Spencer 2010).

Walton-on-the-Naze, Essex

The study site at Walton-on-the-Naze includes a continuous cliffline, extending for 1.2 km in an almost north-south orientation alongshore. The cliffline ranges in elevation from just 2 m

ODN in the north to over 22 m in the south. To the immediate south, the cliffline has ongoing protection with rock revetments and large groynes which offer cliff base protection from wave attack as well as enabling a beach to be kept in place. However there is a 1 km stretch of cliffline to the north where cliffs are unprotected and open to natural forces of retreat. Again these cliffs involve a morphological setting of a more resistant basement deposit (Eocene London Clay) overlain by less resistant sands and gravels of Waltonian Red Crag (Dixon 1979) and more recent Pleistocene deposits from the Anglian Glaciation (Hails and White 1970). The junction between the London Clay and the Red Crag occurs within the cliffs at a variable elevation alongshore, but generally at around 12 m ODN.

The MSTR is just below 5 m ODN at Harwich, slightly lower than for North Norfolk but considerably greater than the tidal range in Suffolk. The cliffline orientation is, however, very similar to the cliffs of Benacre to Southwold although the cliffs are protected from the northerly waves by the landmass that lies to the north. There is a very wide but thin cliff-fronting beach that offers little cliff base protection, and as at the Suffolk site this beach can be removed entirely to expose the London Clay basement platform (Figure 1).

Historic retreat rates at Walton-on-the-Naze have been reported by Gray (1988) for the period 1874 to 1973. Over this period annual retreat rates were 0.68 m a^{-1} in the north and 0.55 m a^{-1} in the south, which Gray (1988) ascribes to differences in cliff elevation and composition, resulting in different modes of retreat. In the north where the cliffs are of lower elevation and less complex stratigraphy, retreat is more continuous and occurs in a parallel fashion, while in the south the cliffs are higher and more complex leading to intermittent processes of periodic retreat and a scalloping in the cliffline due to large scale mass failure. Between 1973 and 1988 cliff retreat was observed to be accelerating (Gray, 1988). In this latter period, based on 3 clifftop positions, Gray (1988) measured retreat rates that averaged to a mean rate of 1.45 m a^{-1}, almost a 3-fold increase on the earlier period.

The shallow nature of the southern North Sea Basin combined with the high frequency of low pressure systems crossing the region regularly generates surges, when water levels are elevated above the predicted semi-diurnal tidal level (Pugh 1987, Lamb 1991). Pye and Blott (2009) report 45 occasions between 1964 and 2008 when the water level at Lowestoft exceeded 2 m ODN. Exceptional surges occurred in 1976, 1978 and 2007 where water levels at Lowestoft reached 2.68 m, 2.33 m and 2.07 m ODN respectively (Steers et al. 1979, Horsburgh et al. 2008). The largest surge on record is that of 1953 (Steers 1953, Muir Wood et al. 2005) when water levels reached 3.44 m ODN at Lowestoft (Rossiter 1954), 2.21 m above the predicted high tide level (Pye and Blott 2009).

The longest reliable historical sea level record is from the Lowestoft tide gauge, which suggests a regional sea level rise of between 2.47 ± 0.23 and 2.57 ± 0.33 mm a^{-1} (1956-2006) (Woodworth et al. 2009). Between 1975 and 2005, sea level recorded by the Lowestoft tide gauge was 13 cm, which equates to an annual rate of 4.3 mm a^{-1} (Pye and Blott 2006). The UK Climate Impacts Programme (UKCIP) predicts future sea level rise in the region to be 69 cm to the 2080s (7.7 mm a^{-1}) (Hulme et al. 2002), while both the UK Government's Department of Environment, Food and Rural Affairs (DEFRA) as well as Halcrow Maritime (1991) suggest a future sea level rise of 6 mm a^{-1}. Considerable debate around sea level rise dynamics, specifically the high level of uncertainty associated with estimating the contribution from large ice sheet melting to global sea level rise, makes these estimates highly uncertain, with a suggestion that global sea level could rise by over 200 cm by 2090-2099 (Woodworth et al. 2011).

Methodology

Selection of time periods of study

Historic maps obtained in electronic format from the UK national mapping agency, the Ordnance Survey (www.edina.ac.uk/digimap) provided a general overview of long-term coastline change at the three study sites since the 1880s. Within this long-term context, short-term shoreline retreat was established for the time periods 1992 – 2000, 2000 – 2008 and 2008 – 2011. 1992 represents the first year for which high resolution cross-shore profiles and high quality vertical aerial photography are available for all the study sites from the UK Environment Agency (Anglian Region) Sea Defence Management Study (UK EA SDMS). 2008 represents the first year for which detailed field studies by the authors are available to supplement the analysis of remotely sensed imagery, with further detailed field surveys in

2011. 2000 is the mid-point of the 1992 – 2008 analysis period and generates two record lengths of 8 years which are appropriate in the context of the cliffline retreat rates observed across the three sites.

Shoreline retreat: Cross-shore profiles and aerial photography

Clifftop edge positions, from high precision dGPS (locational and elevational accuracy of 0.02 and 0.2 m respectively), were extracted from cross-shore profiles surveyed in summer 1992, summer 2000 and summer 2008 by the UK Environment Agency. The EA profiles are located at 1 km alongshore spacing; thus the Weybourne – Sheringham, Benacre-Southwold and Walton-on-the-Naze study sites were characterised by 3, 7 and 2 cross-shore profiles respectively. These at-a-point cross-profiles were then used as tie points against which an alongshore analysis of changing cliffline position was obtained from aerial photography.

Aerial photography taken in summer 1992, 2000 and 2008 was georeferenced within ArcMap 9.2 (www.esri.com) using the British National Grid co-ordinate system (OSGB36) (methodology of Brooks and Spencer 2010). Georeferencing errors across the three study sites were calculated as 2.08% of the total retreat distance between 1992 and 2008. The readily-identifiable edge of the cliff top was digitised on successive photographs and the resulting ‘shoreline’ input into the Digital Shoreline Analysis System Version 3.0 (DSAS) (Thieler et al. 2005). Shore-normal transects were cast at 10 m spacing alongshore to calculate the End Point Rate (EPR) (m a^{-1}), the difference between shoreline positions at two time periods divided by the number of years separating the two periods. In all, the cliffs of Weybourne-Sheringham, Benacre-Southwold and Walton-on-the-Naze included 388, 800 and 100 transects respectively. The EPR was found for each of these individual transects between 1992 and 2008, as well as for the periods 1992-2000 and 2000-2008.

Shoreline retreat: Field surveys

In the recent period since 2008 a series of field surveys was carried out, particularly focussed at Covehithe, as this cliffline has the highest rates of retreat of all the clifflines in the region. Field visits consisted of obtaining a detailed photographic record of change, comprehensive survey of cliff profiles (particularly concentrated at the cliff base) as well as dGPS surveys of the clifftop edge. These field surveys commenced at Covehithe in October 2008, followed by 5 further surveys up until July 2011, developing a detailed record of clifftop retreat along the whole of the Covehithe cliffline. Of particular importance was a dGPS survey of the cliffline in January 2011, which enabled the retreat to be quantified immediately following a period high storminess, with one storm in particular in November 2010 creating cliff failure that was observed in its immediate aftermath (Brooks et al. 2012). The Weybourne- Sheringham cliffs were visited in August 2011 and January 2013 while visits to Walton-on-the-Naze took place in both September and March 2012.

Cliff sediment release

Following quantification of shoreline retreat, the second stage in the analysis involved estimating associated sediment release for the three cliff systems utilising topographic 'NextMap' datasets (from UK NERC Earth Observation Data Centre (NEODC)). Tiles dtm-tg14 (Weybourne-Sheringham), dtm- tm-57 and dtm-tm58 (Benacre-Southwold) and dtm-tm22 (Walton-on-the-Naze) were used to obtain spot heights of the cliff elevations at the same 10 metre alongshore spacing as defined for each transect in the DSAS analysis reported above. The elevations were then multiplied by the retreat rate (EPR) for each transect for the periods 1992 - 2000 and 2000 - 2008 to obtain annual volumetric loss (m^3 sediment a^{-1}) in the cliffs for these two time periods.

Climatic variability index: North Atlantic Oscillation

Values for the monthly NAO for October, November, December, January, February and March from October 1992 to March 2011 were obtained from the Climate Research Unit, University of East Anglia, UK (http://www.cru.uea.ac.uk/cru/data/nao/). These relate to sea-level pressure difference between Gibraltar and Reykjavik, Iceland (Jones et al. 1997). These monthly indices were divided into three periods 1992-2000, 2000-2008 and 2008-11, and the values were plotted for each of the winter months. The first two periods in this analysis corresponded with the analysis of the shoreline retreat and sediment release, while the latter period covered the recent period when shoreline retreat was determined for the Suffolk cliffs through field survey.

Results

Average long-term (1880s – 2010) shoreline retreat rates found for Weybourne-Sheringham, Benacre-Southwold and Walton-on-the-Naze were 1.2 m a^{-1}, 3.1 m a^{-1} and 0.75 m a^{-1} respectively. These averages are for the entire alongshore section; for both Benacre-Southwold and Walton-on-the-Naze they conceal significant alongshore trends in retreat rate.

At the northern end of the Covehithe cliffs, for example, long-term retreat rates have been as high as 4.2 m a^{-1}, while at the southernmost end of the Easton Cliffs rates they have been consistently lower at 2.1 m a^{-1}. Likewise at Walton-on-the-Naze, retreat rates have been higher in the northern section of the cliffline (at 1.1 m a^{-1}) compared with the southern end (0.4 m a^{-1}).Furthermore, as well as concealing underlying spatial trends, calculation of average long-term retreat rates masks considerable temporal variability which requires more detailed assessment.

Between 1992 and 2008, clifftop retreat rates were highest in the Suffolk cliffs (EA cross-profiles SWD2 – SWD7) and lowest in the cliffs of North Norfolk (N2B6 – N2A1), with Walton-on-the-Naze (E1C5) having rates close to, but slightly higher than, those of North Norfolk (Figure 2). Disaggregation of this time period into the periods 1992 – 2000 and 2000 – 2008 shows that there was a switch from high rates of shoreline retreat in the 1990s to lower rates in the 2000s. This is evident at all three study sites (Figure 2).

Using the DSAS methodology to assess shoreline change at 10 m alongshore intervals, shows that the at-a-point record has been indicative of the behaviour of the entire length of cliffline in each of the three cliff systems. At Weybourne-Sheringham, the cliffline showed retreat rates below 1 m a^{-1} between 1992 and 2008, below the long-term (1880s – 2010) mean rate of 1.2 m a^{-1}. For the period 1992 – 2000, the mean alongshore retreat rate was 0.56 m a^{-1} whereas for the period 2000 – 2008 it was 0.08 m a^{-1} (Figure 3a). The difference between these higher and lower rates was thus an order of magnitude, particularly at the eastern end of this cliff system. For the four cliffed sections between Benacre and Southwold, cliffline retreat between 1992 and 2008 varied from ca. 7 m a^{-1} in the north to ca. 3 m a^{-1} in the south. For the period 1992 – 2000, the mean alongshore retreat rate was 5.47 m a^{-1} whereas for the period 2000 – 2008 it was 2.25 m a^{-1} (Figure 3b). This record shows, therefore, a phase when retreat was much higher than the historic rate followed by a phase when retreat was considerably lower than the long-term mean. Recession rates at Walton-on-the-Naze were between 1 and 2 m a^{-1} between 1992 and 2008, again with a trend towards lower retreat rates in the south. For the period 1992 – 2000, the mean alongshore retreat rate was 1.76 m a^{-1} whereas for the period 2000 – 2008 it was 1.13 m a^{-1} (Figure 3c), similar to the long-term mean retreat rate of 1.2 m a^{-1}.

Changes in shoreline retreat rates have implications for sediment release. Such changes are especially marked where cliffs extend for long distances alongshore at high elevation or where shoreline retreat rates are rapid. The highest cliffs in this study are at Weybourne – Sheringham, closely followed by those of Walton-on-the-Naze. However, the cliffline at Walton is much more restricted in lateral extent. Both clifflines have retreated at similar rates of 0.5 - 2 m a^{-1} in the period 1992 – 2008, with recession at Walton-on-the-Naze being somewhat faster. The cliffs between Benacre and Southwold cover a greater distance alongshore, are somewhat lower in elevation, but retreated at the fastest rates of all the study sites between 1992 and 2008. These differences are reflected in variations in mean annual sediment output for the period 1992 – 2008. Outputs have been estimated at 44 037 m^3 a^{-1} at Weybourne-Sheringham, 171 296 m^3 a^{-1} between Benacre and Southwold and 21 178 m^3 a^{-1} at Walton-on-the-Naze. It is clear that the cliffed sections of the Suffolk coast have supplied the most sediment to the nearshore zone in the period 1992 – 2008, four times the rate of North Norfolk and almost an order of magnitude greater than the rate of sediment supply at Walton-on-the-Naze, due to the combination of their greater cumulative alongshore extent and more rapid retreat rates.

Figure 4 shows the volumetric sediment outputs from each of the cliff sections disaggregated into the periods 1992-2000 and 2000-2008.The total mean annual sediment output is estimated at being 311 457 m^3 a^{-1} in the period 1992-2000 and 161 566 m^3 a^{-1} in the period 2000-2008, a reduction of 48% in the second time period compared to the first. The highest mean annual sediment outputs are estimated for the cliffed sections between Benacre and Southwold in both periods, but with a reduction here in mean annual sediment output of 49% after the year 2000. It is clear that the significant decadal-scale oscillations in retreat rate, evident in all three cliff systems, have important implications for sediment delivery to nearshore environments and alongshore sediment transport pathways on the East Anglian coast.

Discussion

The ability to determine cliffline position at high spatial densification (analysis based on over 1 200 cross-shore transects) over discrete time periods has shown that clear differences in cliffline retreat rate can be identified between 1992 – 2000 and 2000 – 2008 on the UK East Anglian coast. These differences are independent of differences in absolute retreat rate and shoreline orientation. They are also independent of differences in age of materials comprising the cliffed sections, although stratigraphic relations are the same in all three locations, with more resistant basal deposits being overlain with more erodible upper cliffs. The fact that the temporal pattern of cliffline retreat has a regional signal strongly suggests an overriding control by atmospheric and oceanographic processes operating at large spatial scales and with considerable temporal variability.

The search for the likely drivers of the inter-decadal variation in cliffline retreat rates is most likely to be best observed in cliff systems of fast response (Lee 2008). In this study, the most rapid rates of cliffline retreat were seen at the Benacre – Southwold study site, with a halving of the recession rate in the period 2000 – 2008 compared to 1992 – 2000. Previous research on the Suffolk has argued for the key role of storm surges in triggering phases of accelerated shoreline retreat (Steers 1953, Williams 1956, Pye and Blott 2006). The largest 20 surge events (with water levels greater than 2.0 m ODN) can be identified from the Lowestoft tidegauge in the period 1992 – 2008. 10 occurred in the 1990s and 10 in the 2000s. However, these events in these two decades were very different in character: the surges of the 1990s were often accompanied by rough sea conditions, with onshore winds in excess of 15.4 m s^{-1} (30kn, Beaufort Force 7, 'near gale') and rainfall of over 40 mm. Such conditions did not occur at all between 2000 and 2008. Furthermore, detailed studies of a period of rapid shoreline retreat at Covehithe in the winter of 2010 – 2011 identified the likely controls as a combination of elevated sea level, near gale-force onshore (i.e. easterly) winds and high rainfall (Brooks et al. 2012). Importantly, it appears that these differences can be linked to variations in the North Atlantic Oscillation (NAO).

The *average* winter (October – March) NAO was higher (more positive) in the 1990s than during the 2000s, reaching the highest mean winter value on record in the early 1990s. However, recent research has considered the link between the average winter NAO index and shoreline change for the Lincolnshire Coast of the east coast of England (a similar setting to those contained within this paper) but has found it to be a poor indicator of storminess for this region (Montreuil and Bullard, 2012). A positive average winter NAO index was not found to be associated with large shoreline change as these shorelines are not vulnerable to the strong westerly winds that typify such phases. However, the average winter index can mask more detailed variations in the index, which can affect the weather patterns over the UK and its margins at daily, weekly and monthly timescales. Figure 5 shows the monthly NAO index between 1992 and 2011, separated into the two phases in which retreat rates were calculated and including the more recent period in which retreat at Covehithe was found to be 11.34 m over a 500 m length of coastline. Like the annual means, the monthly values also suggest that there were periods of strong positive NAO phases during the 1990s, with 6 months having an index value greater than 3. This compares with 2 months when the NAO index was greater than 3 in the 2000s. In the most recent period since 2008, there have been no months with such high positive NAO values. The early 1990s was also a period of very strongly negative phases, with 5 months between 1992 and 1996 having NAO values lower than -3. By contrast, just one month between 2000 and 2008 showed such a strongly negative value. In the most recent period (2008 – 2011), when retreat at Covehithe was particularly high, there were four months of extreme negative NAO values. Two of these months were November and December 2010, while the NAO monthly index for October 2010 had a value of -2.41. It seems intuitive to suggest that strongly positive NAO phases will enhance coastal responses, due to increases in water level, wind speed and wave height consequent upon dominantly cyclonic atmospheric conditions (Keim et al. 2004). However, it has been argued that high amplitude fluctuations in the NAO from extreme positive to extreme negative values may also be important in generating patterns of storminess (Dawson et al. 2010). Thus in particular circumstances the strongly negative phases of the NAO can also be important drivers of shoreline response. Similar findings have been reported for the Danube Delta (Vespremeanu-Stroe et al. 2007) and Romanian Black Sea coastal responses (Vespremeanu-Stroe and Tatui 2011).

The event generating high cliff retreat at Covehithe in November 2010 when the NAO was strongly negative in value has been documented by Brooks et al. (2012). A well-developed, slowly moving low pressure system crossed the UK over a 48-hour period. The eastward-tracking system developed strong winds (>15.4 m s^{-1}) and associated high waves (maximum 3.4 m in 20 m water depth at Southwold), along with high rainfall (45.3 mm at Westleton). The persistence of the storm meant that strong winds coincided with high tide on four consecutive high spring tides, generating waves exceeding 2 m at Southwold, with maximum wave heights of 3.4 m. The low pressure system was slowed by blocking anticyclonic conditions to the north east. Importantly, this blocking anticyclone diverted the low pressure system onto a south easterly track, which was accompanied by winds veering onshore from a north-easterly direction. The synoptic conditions associated with this event were similar to those reported for both the 31 January – 1 February 1953 storm surge (Pye and Blott 2009) where cliffline retreat at Covehithe was over 12 m (Steers 1953) and the 11 January 1978 event where there was also significant recession at this location (Steers et al. 1979). It is suggested that southeast tracking and southern North Sea events (typology of Muir Wood et al. 2005) contain all of the main components leading to high retreat rates in the cliffs of East Anglia; these are commonly associated with low pressure systems that cross the region when the NAO is in a negative phase. In this phase there is greater likelihood of blocking high pressure being present over northern Europe (Hurrell 1995), although the complexities of the North Atlantic atmospheric circulation are not readily described by a single index. By contrast, in positive phases of the NAO circulation is vigorous and low pressure systems can generate strong winds and high surge water levels. Such events may lead to high retreat on eastern coasts (such as the eastward tracking event of 2 – 3 January 1976), but in general such systems are more likely to be damaging to west-facing shorelines (Montreuil and Bullard, 2012). Hence shoreline change can be greater under both strongly positive and negative NAO phases, the coastal response depending upon the storm (hence NAO phase) characteristics that prevail, and how these characteristics vary over decadal and multi-decadal timescales.

Conclusions

Soft rock cliffs are found in many areas of the world and retreat at rates of over 1 m a^{-1}; in many cases retreat rates of 10 m a^{-1} are not uncommon. Decadal-scale variability is evident in all the unprotected retreating soft rock cliffs examined in this study. Retreat rates are not linear; rather, significant oscillations can be seen in the rate of recession around long-term means. For sound planning and policy making at such cliffed coastal margins, information needs to be gathered over sufficiently long timescales to encompass the range of possible retreat rates that might be encountered. In particular, the dangers of decision making based on data collection in periods when coastal change is taking place at less than the long-term mean rate of change should be apparent from the analysis contained in this paper; these dangers are not trivial. In addition, it is clear that these variations in recession rate are accompanied by equally significant variations in the supply of sediments to the nearshore zone, in fluctuations in alongshore sediment transport rates and ultimately in changes to wave attenuation and water circulation patterns associated with down-drift loci of sediment deposition. As yet, however, too little recognition of this variability has found its way into nearshore sediment transport modelling (HR Wallingford 2002).

Furthermore, an understanding of soft rock cliff dynamics can provide an alternative, additional perspective to the well-established view of accelerated sea level rise as the main driver of a linear acceleration in the rate of shoreline change. Historic, and even predicted near-future, rates of sea-level change, measured in units of mm a^{-1}, are very small when considered against the tidal variation in water level, the storm surge residuals that can develop in association with low pressure systems, and the maximum wave heights that can be attained at the coast. Accelerated sea level rise is of course of concern in the long-term, especially for regions where flood risk is substantial, but a preoccupation with this control as the major driver of coastal change should not detract from other forcing factors of significance. Policy making and coastal management practices should address the issue of variability in storminess that accompanies decadal and multi-decadal scale variation in atmospheric circulation systems. It should also engage with the major challenge of the manner in which this variability might itself change under future scenarios of climate and sea level change.

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List of Figures

Figure 1: Study site on the East Anglian coast. A: the coastline of eastern England in the British Isles; B: the coastline of East Anglia, from The Wash embayment (top left of inset box) to the greater Thames estuary (bottom centre); C: the three study saites obn the East Anglian coast and other locations referred to in the text; cliffs and alongshore clifftop profiles (heights in m ODN) at D: Weybourne – Sheringham study site (photograph at Weybourne); E: Benacre-Southwold (photograph at Covehithe); F: Walton-on-the-Naze (photograph towards southern end of cliff section, where cliff heights reach 20 m ODN).

Figure 2: Cross-shore profiles surveyed in summer 1992, summer 2000 and summer 2008 by the UK Environment Agency. Weybourne- Sheringham: N2B6, N2A1; Benacre – Southwold (from north to south): SWD2, SWD3, SWD5, SWD6, SWD7; Walton-on-the-Naze: E1C5.

Figure 3: Alongshore (at 10 m transect spacing) and temporal variation in clifftop retreat rate at the three study sites. The End Point Rate (EPR) (m a^{-1}) the difference between shoreline positions at two time periods divided by the number of years separating the two periods, is plotted for three time intervals at each site: 1992-2000, 2000-2008 and 1992-2008. The range of values in both vertical and horizontal axes should be noted. The broken nature of the Benacre-Southwold plot is explained by the fact that low-lying Broads (no data) divide sections of cliffed shoreline at this locality.

Figure 4: Sediment volume inputs into the nearshore zone for each study site, calculated from the product of clifftop elevation data (from digital terrain models) and clifftop retreat rates (derived from the casting of shore-normal transects) for two time periods, aggregated from individual estimates at 10 m spacing alongshore. Left panel: 1992-2000; right panel: 2000-2008.

Figure 5: Variation in the NAO Index for the months October to March for the years 1992-1993 to 2010-2011. Large closed circles indicate strong (≥ 3.0) positive values of the Index, large open circles show strong (≥ -3.0) negative values. Vertical divisions indicate the time periods of analysis of clifftop retreat in this paper: 1992 – 2000, 2000 – 2008, 2008 – 2010.

figure 1

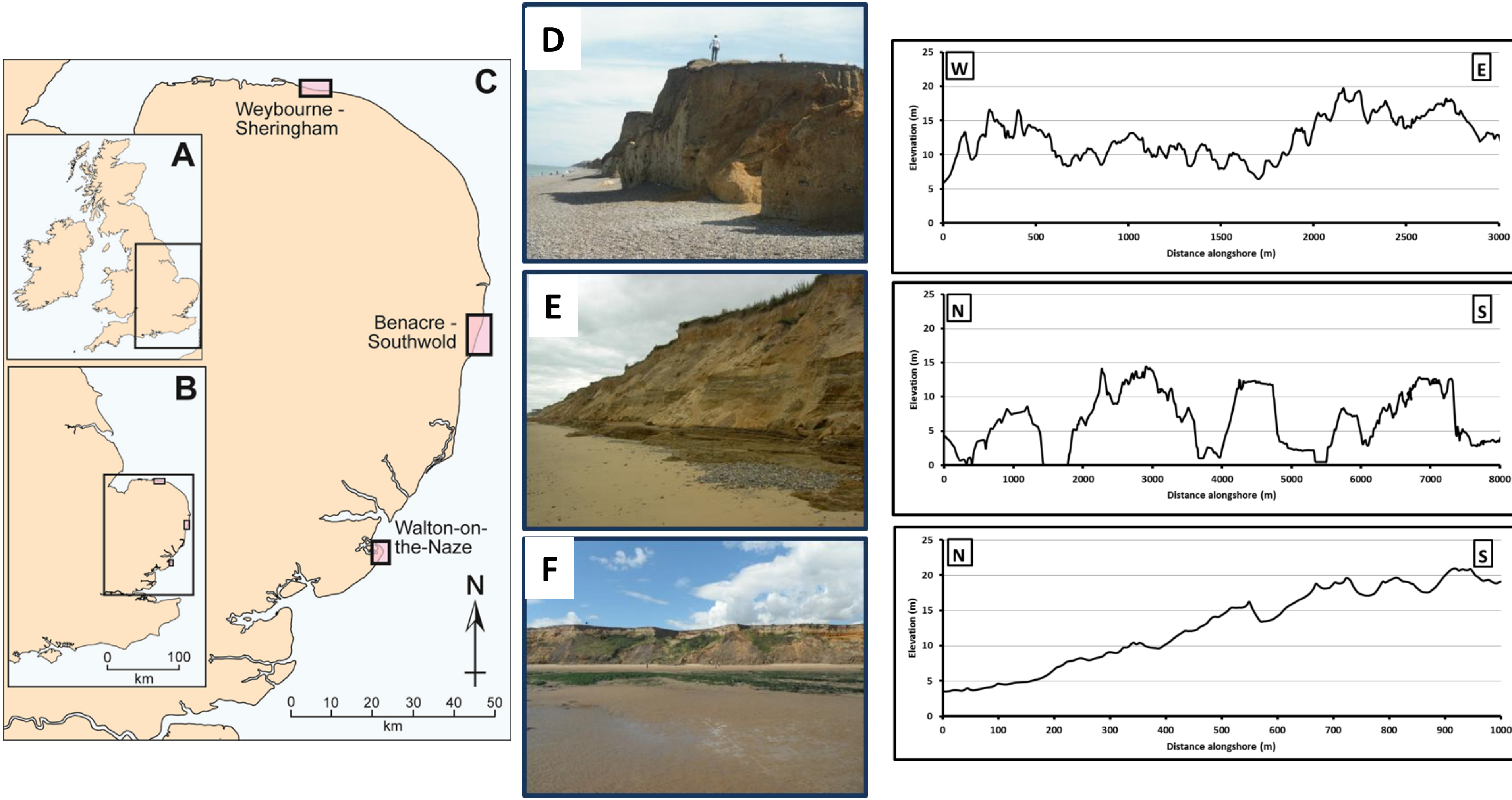

A
B
0
100
km
C
Weybourne -
Sheringham
Benacre -
Southwold
Walton-on-
the-Naze
N
0 10 20 30 40 50
km
D
E
F
W
E
Elevnation (m)
Distance alongshore (m)
N
S
Elevation (m)
Distance alongshore (m)
N
S
Elevation (m)
Distance alongshore (m)

figure 2

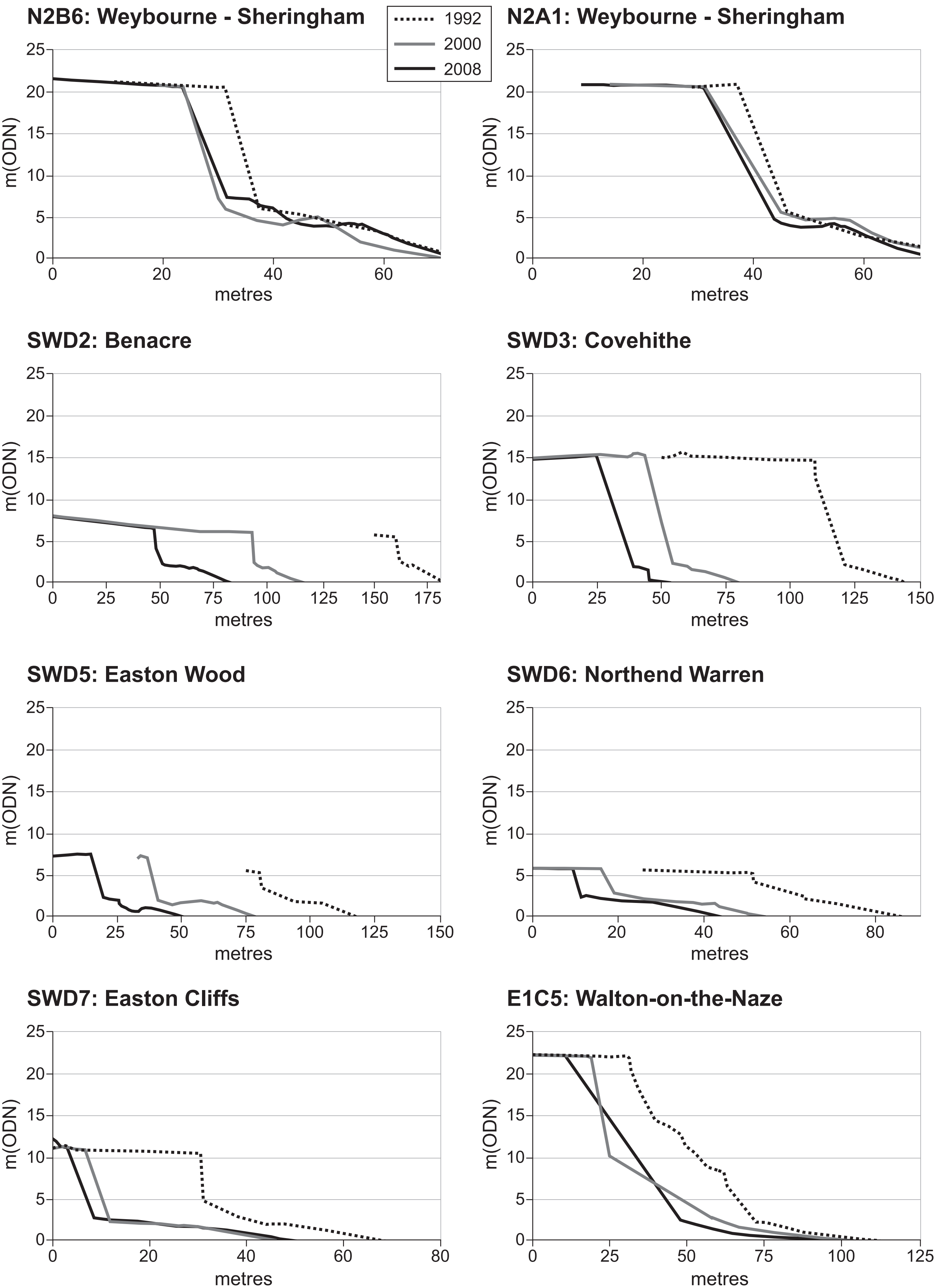

N2B6: Weybourne - Sheringham
1992
2000
2008
N2A1: Weybourne - Sheringham
SWD2: Benacre
SWD3: Covehithe
SWD5: Easton Wood
SWD6: Northend Warren
SWD7: Easton Cliffs
E1C5: Walton-on-the-Naze
m(ODN)
metres
0
5
10
15
20
25
20
40
60
50
75
100
125
150
175
80

figure 3

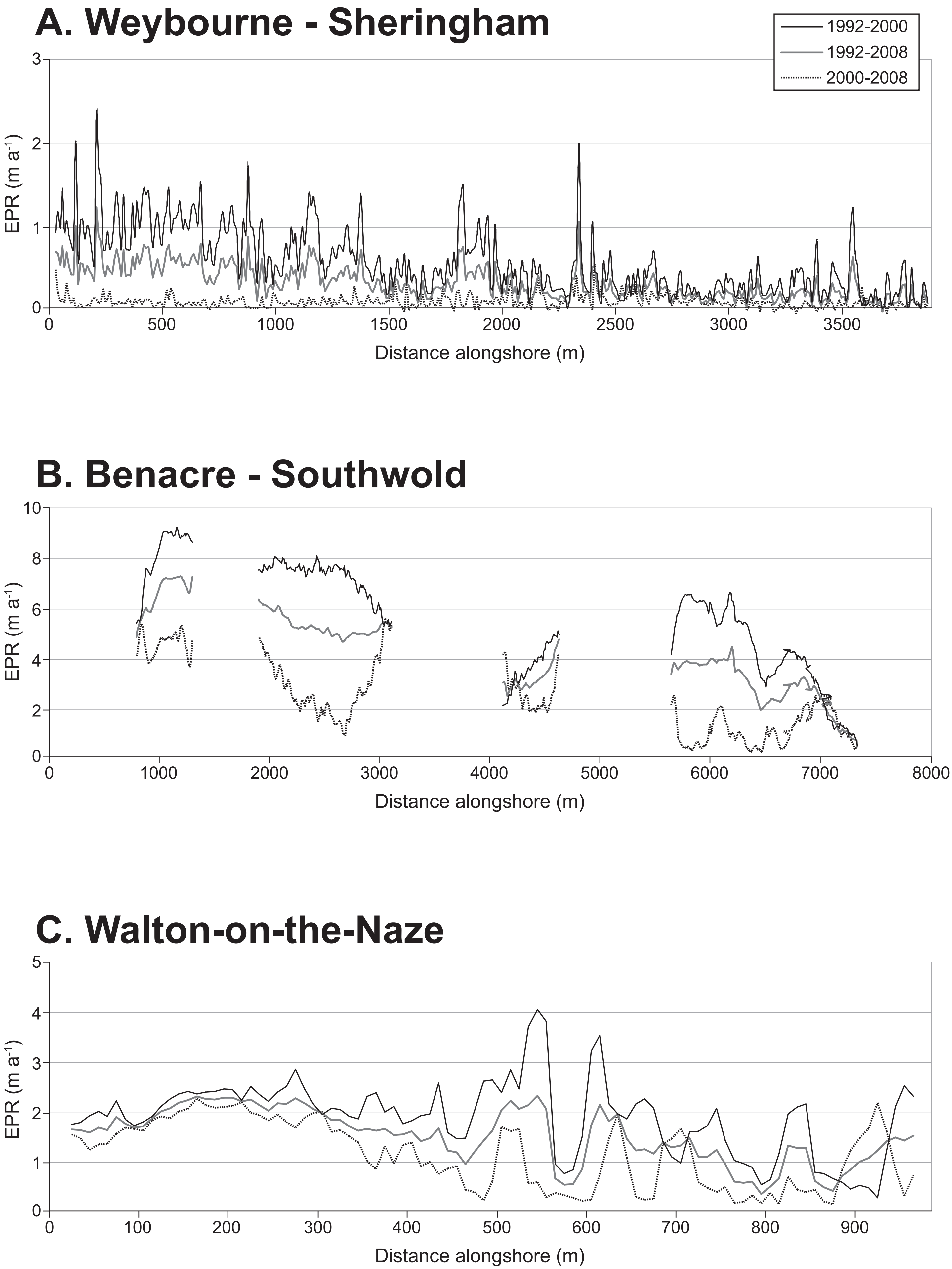

A. Weybourne - Sheringham
1992-2000
1992-2008
2000-2008
EPR (m a-1)
Distance alongshore (m)
B. Benacre - Southwold
EPR (m a-1)
Distance alongshore (m)
C. Walton-on-the-Naze
EPR (m a-1)
Distance alongshore (m)

figure 4

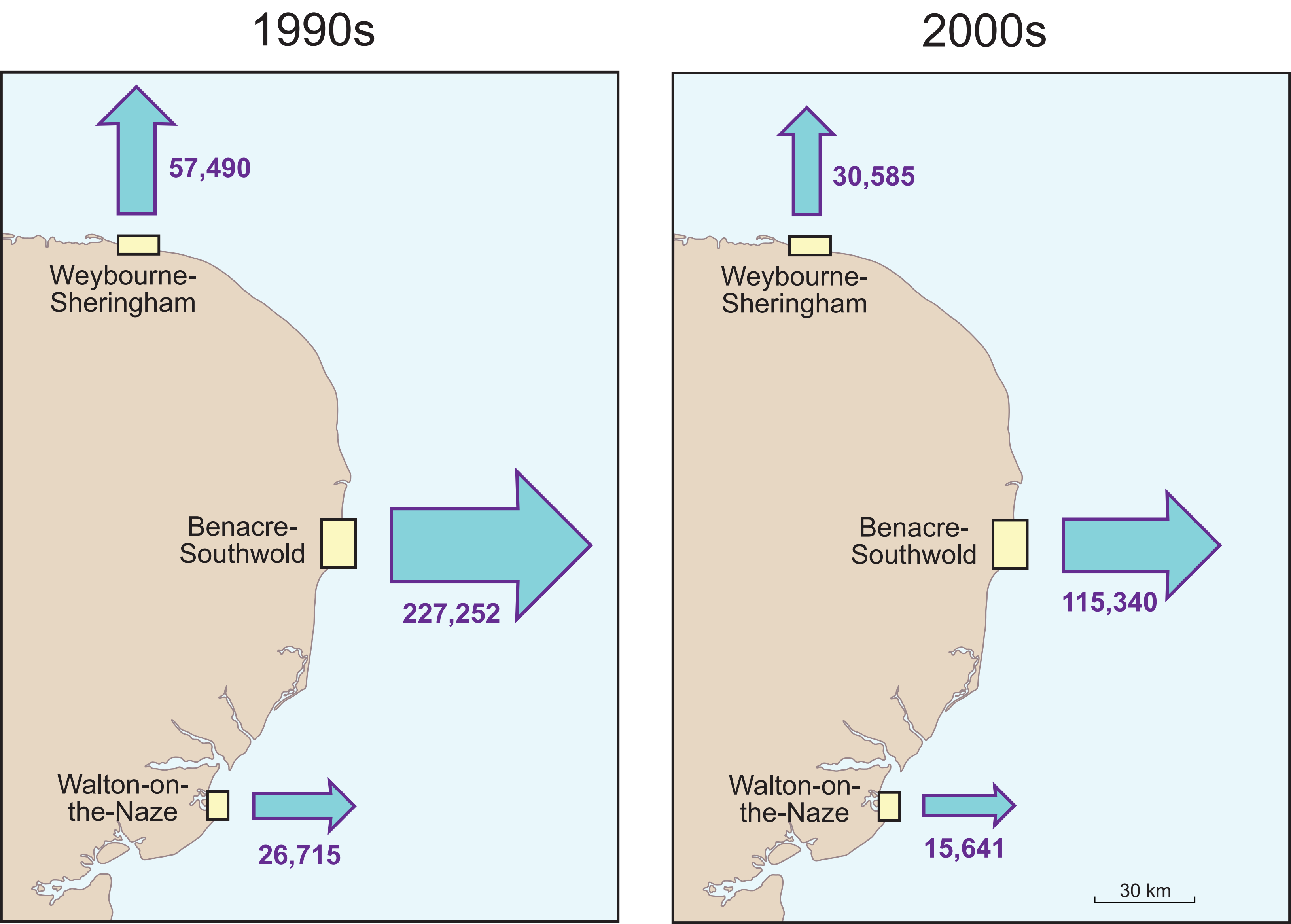
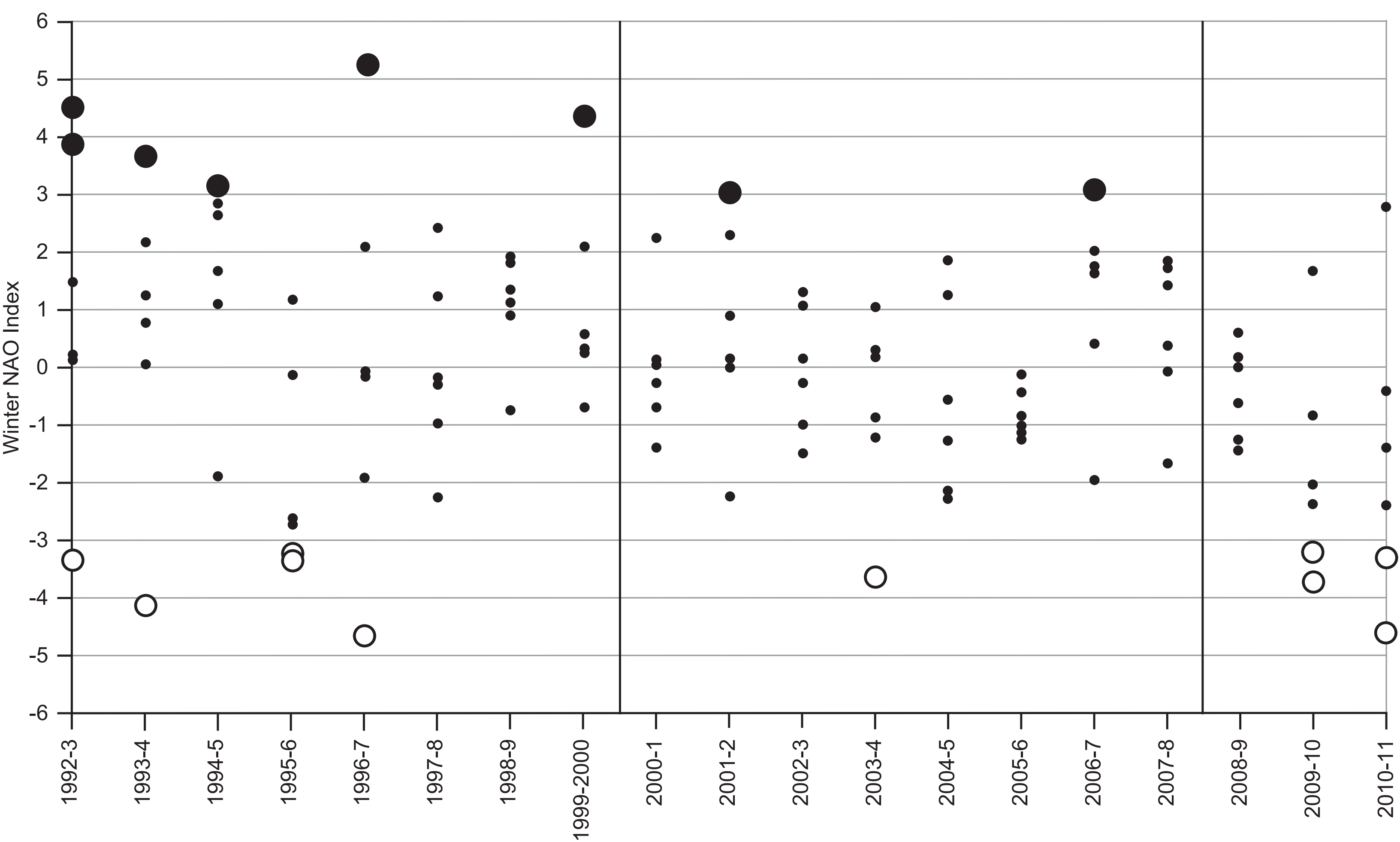

1990s
57,490
Weybourne-
Sheringham
Benacre-
Southwold
227,252
Walton-on-
the-Naze
26,715
2000s
30,585
Weybourne-
Sheringham
Benacre-
Southwold
115,340
Walton-on-
the-Naze
15,641
30 km

figure 5


Winter NAO Index
6
5
4
3
2
1
0
-1
-2
-3
-4
-5
-6
1992-3
1993-4
1994-5
1995-6
1996-7
1997-8
1998-9
1999-2000
2000-1
2001-2
2002-3
2003-4
2004-5
2005-6
2006-7
2007-8
2008-9
2009-10
2010-11